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Forecasting *Helicoverpa armigera* (Lepidoptera: Noctuidae) larval phenology in pigeonpea and chickpea crops using growing degree days

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ABSTRACT

Gram pod borer, *Helicoverpa armigera* is a serious insect pest of pigeonpea and chickpea crops, responsible for huge economic losses. Timely forecasting and subsequent sensible management practices of *H. armigera* would save the crops from economic damage. In the present study, *H. armigera* larval incidence data was recorded from sixteen pigeonpea and chickpea growing locations (Maharashtra, India) for three seasons (2015, 2016 and 2017). Observed accumulated GDD (from 40 SMW to 7 SMW) revealed, *H. armigera* completed one generation in 29 days to develop 4 generations across the locations and seasons. After accumulating 86GDD (40 SMW) and 62 GDD (43 SMW), larval 'biofix' (initial incidence of larvae) was started in pigeonpea and chickpea, respectively. Logistic regression model estimated accumulated GDD required by *H. armigera* larvae to reach ETL in pigeonpea (629 GDD) and chickpea (378 GDD), which was same as observed accumulated GDD. Statistical criteria *viz*., Adjusted r^2, AIC and BIC projected logistic regression model as a better performer in most cases. The geographically unique models developed based on biofix and accumulated GDD in this study can be used for timely advisories and sustainable management of *H. armigera* in pigeonpea and chickpea crops after field validation.

Key words: AIC, Boltzmann, BIC, biofix, logistic, regression

Pigeonpea [*Cajanus cajan* (L.)] is the sixth most important legume crop in the world. India and Myanmar are the major producers (83%) ahead of Malawi, Tanzania, Kenya and Uganda. Chickpea (*Cicer arietinum* L.) is the widely cultivated food legume in South Asia and the third largest food legume produced globally. Worldwide, chickpea production averaged 12.09 million tons in 2016. India is a major producer (70%) over Turkey, Pakistan, Australia, Myanmar, Ethiopia, Iran, Mexico, Canada and United states (FAOSTAT, 2018). More than 200 species of insects feed on chickpea and pigeonpea crops. Most of the insects have a sporadic or restricted distribution, or seldom present at high densities to cause economic losses. On the other hand, some arthropods are devastating on both the crops. One such insect pest is gram pod borer *H. armigera*, the most important constraint to pulse production in Asia, Africa, Australia, and the Mediterranean Europe. A monetary loss in chickpea and pigeonpea worldwide due to *H.armigera* alone was estimated at more than US$600 million annually, in spite of several plant protection interventions (Rao *et al*., 2013).

In India, *H. armigera* has a large number of alternate hosts like chickpea, pigeonpea, marigold, chilli, okra, cottonetc. Genetic Engineering Approval Committee (GEAC) of Government of India (GOI) approved pigeonpea as a refuge crop for *Bt* cotton (Yenagi *et. al.,* 2011). Host availability alone does not determine the abundance and distribution of *H. armigera*; factors like topography, farming practices and climate change will affect the relative phenology and survival. Mironidis and Savopoulou-Soultani (2008) reported that alternating temperature conditions allow *H. armigera* to complete its life cycle over a much wider range of temperature levels than do constant conditions. Phenologies of some insects are changed by climate change (Westgarth-Smith *et al.,* 2007; Parmesan, 2007). Srinivasa Rao and Prasad (2020) observed growth and development of *Spodoptera litura* are significantly influenced by both lower and higher temperature.

There is a mounting demand for forecasting seasonal occurrence of insects and many mathematical models were developed that describe developmental rates as a function

of temperature (Wagner *et al.,* 1984). Degree-day models are widely used to predict crop pests and diseases incidence to advocate timely control strategies (Chen *et al.,* 2013). Ziter *et al.* (2012) opined that models developed on degree-days are sufficient evidences to capture certain important aspects of the biology of insect pests, and are therefore useful abstractions. Chen *et al.* (2015) observed that change in diurnal temperature range could substantially alter insect life history. Much is known about phenologies of incubating eggs (Dhillon and Sharma, 2007), overwintering pupae (Huang and Li, 2014) and flying adults (Sharpe and DeMichele, 1977) of *H. armigera* worldwide. Yet, forecasting of *H. armigera* larvae as function of growing degree-days has not been modeled on pigeonpea and chickpea. In this study we tried to advance the existing information to forecast the *H. armigera* larval phenology in pigeonpea and chickpea through degree-days estimation.

MATERIALS AND METHODS

Study sites and sampling

Sampling was carried out in sixteen locations (districts) of Maharashtra state, situated in the western and eastern plateau and hills agro-climatic zones of India (Fig.1). From each location, fifty villages were selected with one acre ($4000m^2$) as a unit of observation in each village. Fixed plot survey was carried daily in selected units during three successive seasons (2015, 2016 and 2017) starting from October to February in pigeonpea and chickpea crops. The selected units were ensured with good agronomic practices to keep the crop healthy withstanding insecticidal spray. Sampling varied with the crop. In pigeonpea, randomly ten plants were selected from each unit and from each plant three branches located in different directions from middle portion of the plant were selected. The number of larvae per 3 branches was ascertained. In chickpea, number of larvae per one meter row length was observed from selected five random places in the field. Daily average number of larvae on respective crops from each unit in a district was represented as mean larval number per location in a day. Further, mean larval number per location for each Standard Meteorological Week (SMW) was averaged in pigeonpea (from 40 to 03 SMW) and chickpea (from 43 to 07 SMW) crops. In both the crops, observation was targeted on 3^{rd} in star larvae only as they spent 20% more time feeding than first instars (Johnson and Zalucki, 2007). Initial larval appearance (biofix) of *H. armigera* across the locations in two crops has been noticed for further model evaluation.

Temperature data sets and calculation of Growing Degree Days(GDD)

Weather data was obtained from ICAR-Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, India for the study period (2015 to 2017). Laboratory study conducted by Mironidis and Savopoulou-Soultani (2008) showed, that at constant temperatures outside the 17.5-32.5ºC range did not develop *H. armigera* from egg to adult (emergence), while alternating conditions expanded this range from 10 to 35ºC. In the present study, the Lower Development Threshold (LDT) temperature 12.6ºC (Hartstack *et al.*, 1976) specific to *H. armigera* was considered for calculating GDD, while upper temperature threshold was set to 42ºC. A more precise method-sine wave curve horizontal cut-off method was used to compute GDD. This method takes the daily minimum, maximum, and baseline temperatures (lower threshold) to estimate the GDD (http://ipm.ucanr.edu/WEATHER/index.html).Expected number of *H. armigera* generations and generation time was estimated by considering GDD required for completing one generation time (from egg to adult stage) i.e., 422.3 degree-days (Hartstack *et al*., 1976). Based on biofix and LDT, growing degree-days required by *H. armigera* to attain Economic Threshold Level (ETL) was computed across the locations in pigeonpea and chickpea crops.

Generations and generation time

A two-way analysis of variance (ANOVA) was performed to determine the influence of seasons and locations on mean larval number on pigeonpea and chickpea, Temperature Maximum (Tmax.), Temperature Minimum (Tmin.), GDD, Generation (G) and Generation Time (GT). The observed cumulative mean larval number and estimated accumulated GDD were subjected to ANOVA for each month separately. Tukey's multiple comparison test was employed to compare means and Levene's test for analyzing homogeneity of variance (Sokal and Rohlf, 1995).

Fitting phenological models

The non-linear regression models (Boltzmann and Logistic equations) developed by Damos and Savopoulou-Soultani (2010) were employed to describe the relationship between accumulated GDD and the larval cumulative incidence. In order to assess assumptions of independency and normality of the error term, a residual analysis was performed (Sokal and Rohlf, 1995).

Based on three parameters 'Boltzmann' type equation

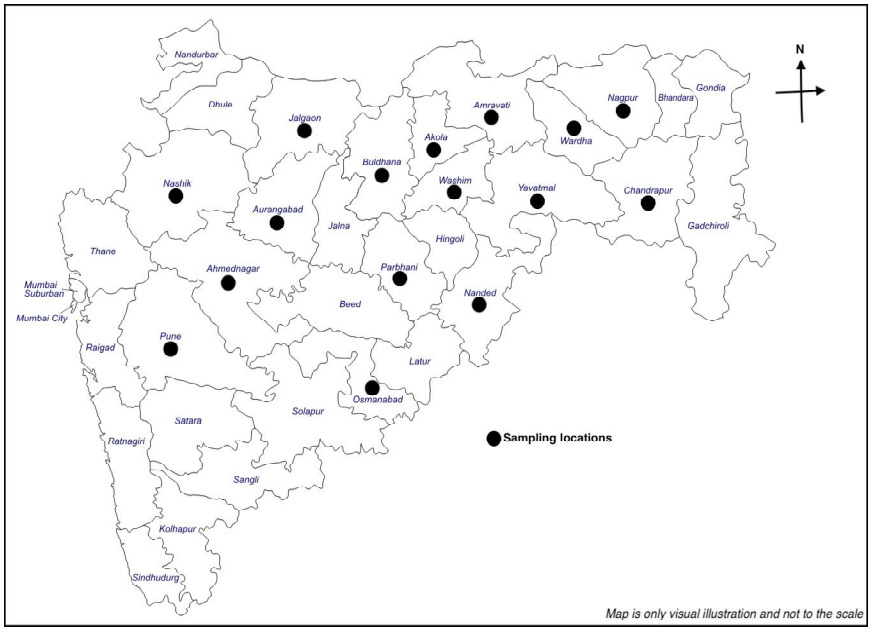


Fig. 1: Outline map of Maharashtra state representing sampling sites

was fitted to data. $f(x) = \frac{a}{1+e^{((-x-c)/b)}}$ (1)

Based on a four parameters 'Logistic' type regression function was fitted to data.

$$g(x) = d + \frac{a}{1+\left[\frac{x}{c}\right]^b} \quad (2)$$

In all the cases, parameter estimation was based on an iterative Ordinary Least Square (OLS) method, using the Levenberge-Marquard algorithm, in which the observed cumulative larval number was treated as the dependent variable. Regressed predicted values and residuals were obtained by fitting above equations with the respective observed cumulative larval number and estimated parameters (SPSS, 1997). Both Eq. (1) and Eq. (2) were fitted with estimated parameters and the number of accumulated GDD required for *H. armigera* to reach ETL was observed. Further, the estimated GDD was compared with natural GDD accumulation needed to attain ETL in field condition.

Statistical evaluation of model

The models developed were fitted with (both observed and predicted) cumulative larval number and evaluated for performance comparisons, which are based on the adjusted coefficient of determination (Adj. r^2) and on the Akaike's Information Criteria (AIC) and Bayes-Schwartz Information Criteria (BIC) (Kvalseth, 1985; Quinn and Keough, 2002).

Adj. r^2 is defined as:

$$Adjr^2 = 1 - \frac{(RSS/n - (\theta+1))}{SS/n - 1} \quad (3)$$

where *RSS* is the residual sum of squares; *SS*, the total sum of squares; and *n* the number of observations (Kvalseth, 1985; Richmond and Bacheler, 1989). AIC developed and proposed by Akaike (1974) is a measure of the goodness of fit of an estimated statistical model and is grounded on the concept of entropy (Burnham and Anderson, 2002; Quinn and Keough, 2002):

$$AIC = n[ln(RSS)] - [n - 2(\theta+1)] - n\ln(n) \quad (4)$$

The BIC (Schwartz, 1978), is an increasing function of the root mean square error (Quinn and Keough, 2002):

$$BIC = n[\ln(RSS)] + (\theta+1)\ln(n) - n\ln(n) \quad (5)$$

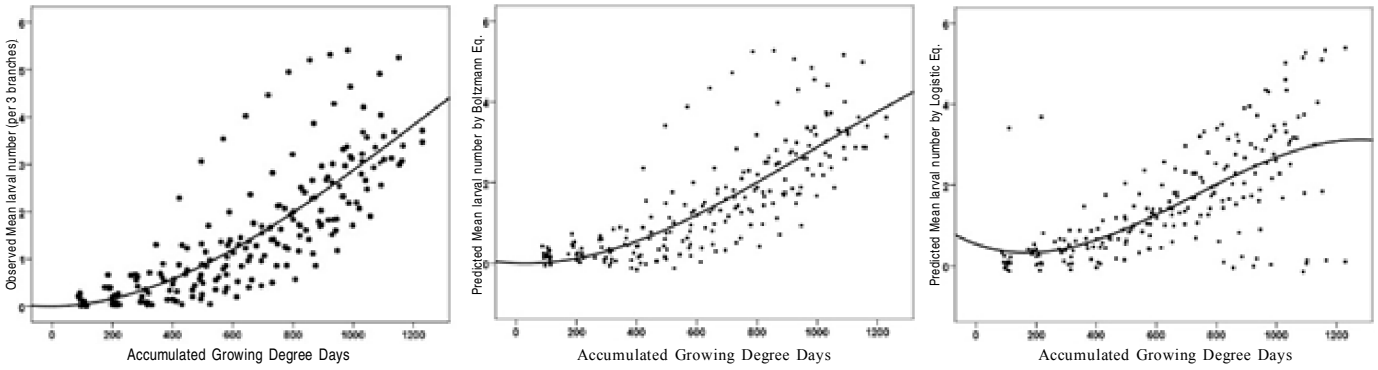
where, *RSS* is the residual sum of squares and *SS* the total sum of squares and *n* the number of observations.

The BIC penalizes free parameters more strongly than does the AIC (Burnham and Anderson, 2002; Quinn and Keough, 2002).

RESULTS AND DISCUSSION

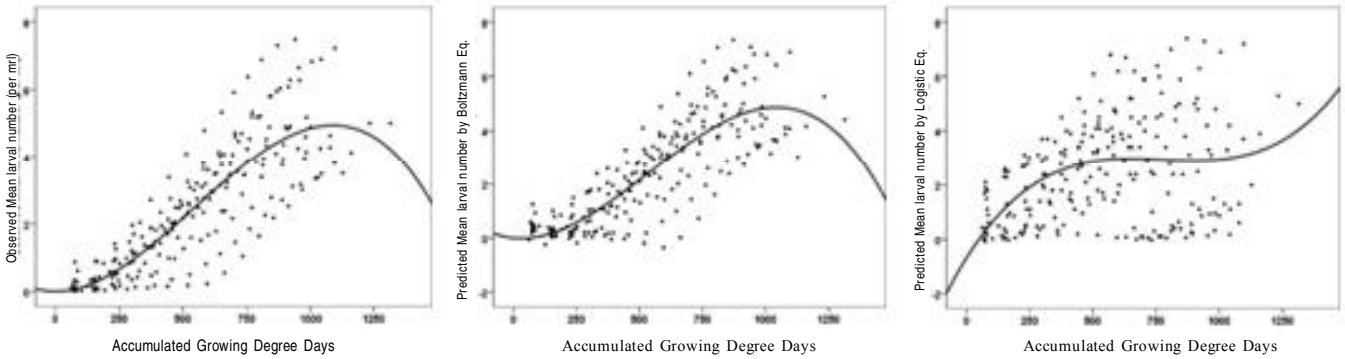
Temperature, generations, generation time and growing degree-days across locations

A considerable variation across sixteen locations and



(a) (b) (c)

Fig. 2: Scattered plot illustrating the pooled model fit of mean larval number per 3 branches with accumulated growing degree-days in pigeonpeain (a) Observed (b) Boltzmann and (c) Logistic equation



(a) (b) (c)

Fig. 3: Scattered plot illustrating the pooled model fit of mean larval number per meter row length with accumulated growing degree-days in chickpea in (a) Observed (b) Boltzmann and (c) Logistic equation

three seasons was observed for minimum (F=6.42; df=2,15; $p<0.05$ and F=20.21; df=2,15; $p<0.05$) and maximum (F=14.34; df=2,15; $p<0.05$ and F=57.24; df=2,15; $p<0.05$) temperatures. Higher minimum and maximum temperatures were noticed in Washim and Jalgaon locations, respectively. Rise in day mean minimum (17.6 ºC) and maximum (32.5 ºC) temperatures were noticed during 2015. The highest estimated mean accumulated GDD were observed at Chandrapur (1716.4) location and during 2015 season (1766.8). There was significant difference (F = 11.16; df=*2,15*; $p<0.05$ and F=187.07; df=*2,15;* $p<0.05$) for accumulated GDD between locations and seasons. Number of generations (F=11.6; df=*2,15;* $p<0.05$ and F=186.88, df=*2,15;* $p<0.05$) and generation time (F=11.64; df=*2,15;* $p<0.05$ and F=169.44, df=*2,15;* $p<0.05$) of *H. armigera* varied considerably between locations and seasons. More number of *H. armigera* generations coupled with shortened generation time was noticed from Chandrapur location (4.07 G; 32.99 days GT) and during 2015 season (4.18 G; 31.9 days GT) (Table 1).

Differences in number of generations and generation time of *H. armigera* across the locations and seasons might be attributed to variations in day mean temperatures. Similar observation was made by Srinivasa Rao *et al*. (2016) on number of generations and generation time of *H. armigera* larva for future climate data on pigeonpea. In current study, erroneous degree-day estimates between locations and seasons was ascribed to changes in day air temperatures, whereas Kuhrt *et al.* (2006) explained the defective estimate of degree-days as a comparable difference between microhabitat and ambient air temperatures. Higher incidence of *H. armigera* larvae on pigeonpea was linked to temperature rise across the locations and seasons, which was supported by laboratory study conducted by Akbar *et al.* (2016), where increased temperature had negative effect on *H. armigera* larval survival, larval period, pupal weight and pupal period, and a positive effect on larval growth. Weather based prediction models of *H. armigera* larval population on soybean developed by Ram Manohar et al. (2019) revealed, maximum temperature (27.48 – 31.44°C) favored their peak incidence. Conversely Mironidis and Savopoulou-Soultani (2008) observed that extreme temperatures had

Table 1: Variation in cumulative mean larval incidence, growing degree days, generations and generation time

Year	Variable	Ahmednagar	Jalgaon	Nasik	Pune	Aurangabad	Nanded	Osmanabad	Parbhani	Akola	Amravati	Buldhana	Chandrapur	Nagpur	Washim	Wardha	Yavatmal	Overall Mean
2015	PP(ML)	0.14	0.03	-	-	0.07	0.04	0.1	0.11	0.25	0.12	0.08	0.15	0.21	0.06	0.15	0.21	0.12
	CP(ML)	0.126	0.087	0.0705	0.2025	0.089	0.1495	0.1495	0.1505	0.218	0.147	0.1105	0.1195	0.2805	0.0935	0.153	0.1825	0.15
	Tmax.	32.25	33.37	31.19	31.67	31.97	33.86	32.16	33.83	33.95	31.83	31.5	32.85	32.26	32.01	33.1	32.28	32.51
	Tmin.	15.66	16.75	15.09	16.1	18.18	15.54	17.03	18.29	18.4	18.21	18.88	19.86	17.55	20.26	18.25	18.29	17.65
	GDD	1613.76	1749.76	1521.11	1607.06	1771.43	1729.88	1714.21	1906.42	1918.99	1754.18	1801.73	1932.45	1705.42	1926.09	1818.51	1798.88	1766.87
	G	3.82	4.14	3.6	3.81	4.19	4.1	4.06	4.51	4.54	4.15	4.27	4.58	4.04	4.56	4.31	4.26	4.18
	GT	34.8	32.1	36.92	34.95	31.71	32.47	32.76	29.46	29.27	32.02	31.17	29.06	32.93	29.16	30.89	31.22	31.93
2016	PP(ML)	0.68	0.35	-	-	0.19	0.56	0.55	0.3	0.17	0.32	0.23	0.36	0.34	0.37	0.71	0.27	0.39
	CP(ML)	0.55	0.43	0.18	0.37	0.31	0.52	0.42	0.34	0.34	0.27	0.3	0.46	0.31	0.59	0.32	0.59	0.39
	Tmax.	31.45	32.02	30.2	30.6	30.78	31.86	30.74	31.44	32.54	30.13	30.07	31.91	31.65	30.22	31.98	30.7	31.14
	Tmin.	13.66	15.04	14	14.64	16.08	17.03	14.86	16.16	16.45	15.31	17.02	17.22	15.51	18.56	16.57	15.76	15.87
	GDD	1327.96	1427.37	1270.07	1347.01	1422.92	1588.74	1384.63	1476.31	1553.08	1322.25	1455.73	1554.81	1397.07	1586.06	1496.44	1402.89	1438.33
	G	3.14	3.38	3.01	3.19	3.37	3.76	3.28	3.5	3.68	3.13	3.45	3.68	3.31	3.76	3.54	3.32	3.41
	GT	42.29	39.35	44.22	41.7	39.47	35.35	40.56	38.04	36.16	42.48	38.58	36.12	40.2	35.41	37.53	40.04	39.22
2017	PP(ML)	0.1	0.17	-	-	0.07	0.06	0.3	0.12	0.11	0.13	0.02	0.1	0.08	0.22	0.08	0.09	0.12
	CP(ML)	0.45	0.23	0.11	0.34	0.19	0.36	0.37	0.15	0.14	0.11	0.09	0.06	0.15	0.1	0.27	0.31	0.21
	Tmax.	31.94	32.45	30.45	30.72	30.79	32.19	30.94	32.22	33.27	30.72	30.68	32.51	31.73	32.36	32.06	32.06	31.69
	Tmin.	14.88	16	14.89	15.82	16.29	17.34	13.88	16.27	17.65	17.71	17.86	18.57	16.14	16.05	17.09	16.93	16.46
	GDD	1442.08	1494.81	1313.47	1402.58	1449.94	1597.6	1328.36	1516.67	1671.06	1522.16	1532.8	1661.83	1449.51	1525.23	1528.78	1550.15	1499.19
	G	3.41	3.54	3.11	3.32	3.43	3.78	3.15	3.59	3.96	3.6	3.63	3.94	3.43	3.61	3.62	3.67	3.55
	GT	38.95	37.57	42.76	40.04	38.74	35.16	42.28	37.03	33.61	36.9	36.64	33.8	38.75	36.82	36.74	36.23	37.63
Overall Mean	PP(ML)	0.31	0.18	-	-	0.11	0.22	0.32	0.18	0.18	0.19	0.11	0.20	0.21	0.22	0.31	0.19	
	CP(ML)	0.38	0.25	0.12	0.30	0.20	0.34	0.31	0.21	0.23	0.18	0.17	0.21	0.25	0.26	0.25	0.36	
	Tmax.	31.88	32.61	30.61	31.00	31.18	32.64	31.28	32.50	33.25	30.89	30.75	32.42	31.88	31.53	32.38	31.68	
	Tmin.	14.73	15.93	14.66	15.52	16.85	16.64	15.26	16.91	17.50	17.08	17.92	18.55	16.40	18.29	17.30	16.99	
	GDD	1461.27	1557.31	1368.22	1452.22	1548.10	1638.74	1475.73	1633.13	1714.38	1532.86	1596.75	1716.36	1517.33	1679.13	1614.58	1583.97	
	G	3.46	3.69	3.24	3.44	3.66	3.88	3.50	3.87	4.06	3.63	3.78	4.07	3.59	3.98	3.82	3.75	
	GT	38.68	36.34	41.30	38.90	36.64	34.33	38.53	34.84	33.01	37.13	35.46	32.99	37.29	33.80	35.05	35.83	

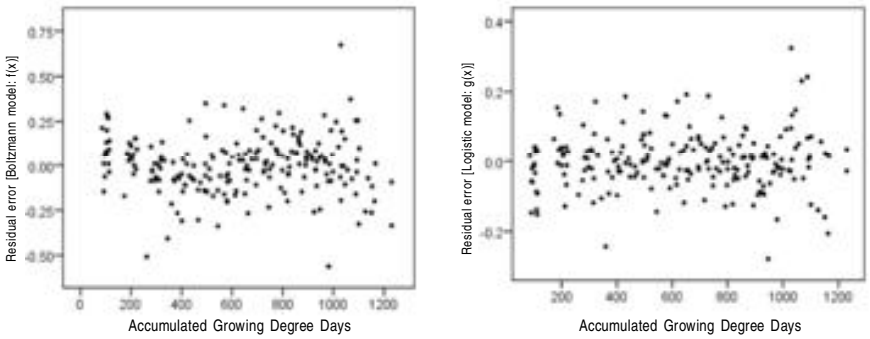
PP – Pigeonpea, CP – Chickpea, ML – Mean Larvae, Tmax. - Temperature maximum, Tmin. - Temperature minimum, GDD - Growing Degree Days from 40th to 7th standard meteorological week, G - Generations and GT - Generation Time

Table 2: Outlining the *H.armigera* larval phenology by parameter estimates (S.E) and coefficient of determination for two non-linear regression models

Location	Parameter estimate (SE)								Location	Parameter estimate (SE)							
	Pigeonpea				Chickpea					Pigeonpea				Chickpea			
	Boltzmann		Logistic		Boltzmann		Logistic			Boltzmann		Logistic		Boltzmann		Logistic	
Ahmednagar	a	-0.110	a	-67.525	a	-164.180	a	11.099	Nanded	a	-0.802	a	-35.558	a	-9.537	a	-10.874
		(0.141)		(217.054)		(518.828)		-(0.931)			(0.147)		(37.119)		(4.689)		(1.214)
	b	-377.555	b	3.068	b	-16907.20	b	2.183		b	-663.709	b	2.200	b	-1602.287	b	2.618
		(26.987)		(0.510)		(58382.98)		(0.155)			(43.247)		(0.176)		(591.680)		(0.230)
	c	-498.673	c	2616.916	c	84228.02	c	719.070		c	-216.001	c	3311.626	c	3488.767	c	839.272
		(51.202)		(3285.557		(350745.88)		(50.690)			(82.859)		(1984.245)		(2103.234)		(68.891)
	R^2	0.994	d	67.910	R^2	0.994	d	11.601		R^2	0.998	d	35.684	R^2	0.989	d	11.019
				(217.009)				(0.868)					(37.097)				(1.160)
			R^2	0.995			R^2	0.999				R^2	0.999	R^2	0.998		
Jalgaon	a	-0.024	a	-4.841	a	-1.437	a	-6.058	Nashik	a	-47.957	a	-2.009	a	-92.954	a	-2.711
		(0.102)		(1.714)		(0636)		(0.430)			(949.690)		(0.790)		(2636.928)		(.370)
	b	-209.862	b	9.144	b	-628.58	b	5.389		b	-27251.321	b	1.998	b	-22918.274	b	2.392
		(25.538)		(2.433)		(126.240)		(0.510)			(526447.731)		(0.990)		(639794.815)		(0.560)
	c	-868.853	c	1055.346	c	-87.892	c	978.470		c	105620.886	c	514.476	c	103877.598	c	267.526
		(32.068)		(85.653)		(285.951)		(28.581)			(2574093.864)		(157.791)		(349698.415)		(23.261)
	R^2	0.975	d	4.990	R^2	0.965	d	6.069		R^2	0.932	d	2.283	R^2	0.921	d	2.661
				(1.691)				(0.403)					(0.647)				(0.256)
	R^2	0.980			R^2	0.995				R^2	0.957			R^2	0.987		
Akola	a	-0.241	a	-5.969	a	-122.446	a	-5.389	Osmanabad	a	-137.391	a	-5.891	a	-11.003	a	-9.519
		(0.107)		(1.281)		(1016.39)		(0.221)			(1311.414)		(0.257)		(6.056)		(0.677)
	b	-315.051	b	4.951	b	-22386.541	b	3.453		b	-21044.386	b	3.285	b	-1760.959	b	2.606
		(31.940)		(0.518)		(182317.841)		(0.232)			(196548.543)		(0.257)		(769.564)		(0.159)
	c	-771.968	c	1155.440	c	-107471.521	c	609.336		c	103512.884	c	516.704	c	4095.806	c	737.735
		(43.166)		(93.095)		(1061912.934)		(14.776)			(1167183.555)		(13.687)		(2799.823)		(38.882)
	R^2	0.988	d	5.970	R^2	0.971	d	5.387		R^2	0.97	d	6.068	R^2	0.989	d	9.546
				(1.267)				(0.189)					(0.208)				(0.641)
	R^2	0.998			R^2	0.998				R^2	0.998			R^2	0.999		
Amravati	a	-1.269	a	-3.614	a	-1.398	a	-4.114	Parbhani	a	-2.004	a	-3.622	a	-117.342	a	-4.791
		(0.779)		(0.295)		(0.717)		(0.163)			(1.149)		(0.221)		(1084.177)		(0.185)
	b	-629.110	b	5.083	b	-675.993	b	5.252		b	-921.787	b	4.168	b	-23584.087	b	3.145
		(196.876)		(0.625)		(177.151)		(0.308)			(328.027)		(0.338)		(213584.208)		(0.205)
	c	-57.771	c	733.697	c	8.658	c	800.324		c	430.166	c	766.122	c	112297.380	c	546.575
		(392.729)		(26.476)		(370.003)		(13.810)			(727.131)		(23.881)		(1234319.800)		(13.205)
	R^2	0.967	d	3.672	R^2	0.963	d	4.202		R^2	0.975	d	3.642	R^2	0.969	d	4.938
				(0.270)				(0.151)					(0.203)				(0.154)
	R^2			0.995			R^2	0.998				R^2	0.998			R^2	0.998

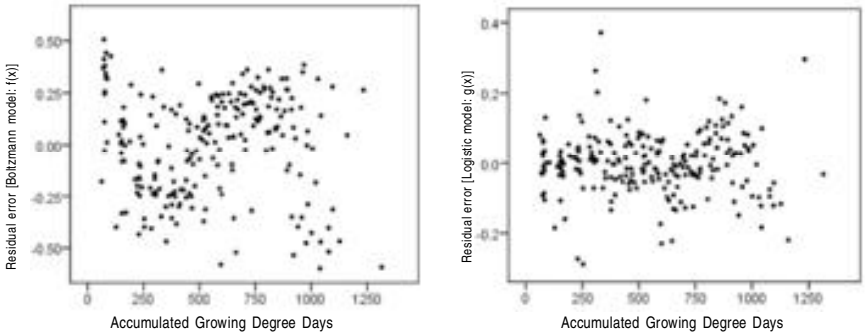
Location	Parameter estimate (SE)				Location	Parameter estimate (SE)			
	Pigeonpea		Chickpea			Pigeonpea		Chickpea	
	Boltzmann	Logistic	Boltzmann	Logistic		Boltzmann	Logistic	Boltzmann	Logistic
Aurangabad	a -24.349 (99.866)	a -2650.184 (3754600.040)	a -130.423 (1634.326)	a -4.617 (0.333)	Pune	a -2.102 (0.351)	a -165.846 (922.996)	a -9.664 (5.511)	a -8.454 (0.352)
	b -12429.071 (49068.745)	b 1.018 (1.045)	b -29461.261 (362569.526)	b 2.312 (0.233)		b -782.788 (66.711)	b 1.715 (0.205)	b -1608.376 (708.017)	b 2.789 (0.109)
	c 39621.303 (207494.955)	c 1151513.929 (161176910.05)	c 143507.069 (2134204.983)	c 505.043 (26.903)		c 513.02 (164.486)	c 7869.606 (28084.415)	c 3555.717 (2504.692)	c 676.321 (19.839)
	R^2 0.987	d 2650.067 (375459958)	R^2 0.969	d 4.827 (0.275)		R^2 0.998	d 165.913 (922.943)	R^2 0.988	d 8.694 (0.332)
	R^2 0.987		R^2 0.997			R^2 0.999		R^2 1.000	
Buldana	a -0.909 (0.400)	a -2.853 (0.501)	a -5.893 (3.721)	a -4.743 (0.423)	Wardha	a -2.012 (0.354)	a -9428.498 (3336692.818)	a -3.452 (2.766)	a -4.934 (0.221)
	b -864.270 (199.104)	b 2.984 (0.379)	b -1853.339 (936.380)	b 2.787 (0.239)		b -898.276 (84.800)	b 1.645 (0.216)	b -1154.724 (529.658)	b 3.961 (0.243)
	c -155.108 (318.803)	c 914.316 (103.691)	c 3135.616 (815.066)	c 740.511 (46.627)		c 530.727 (200.871)	c 121764.322 (2627420.12)	c 1505.904 (1493.814)	c 667.539 (16.114)
	R^2 0.989	d 2.973 (0.483)	R^2 0.985	d 4.720 (0.397)		R^2 0.998	d 9428.493 (3336692.749)	R^2 0.971	d 5.810 (0.201)
	R^2 0.997		R^2 0.998			R^2 0.997		R^2 0.999	
Chandrapur	a -0.848 (0.528)	a -3.672 (0.303)	a -6.152 (4.826)	a -5.009 (0.360)	Washim	a -4.310 (1.762)	a -6.354 (0.746)	a -118.669 (883.119)	a -8.275 (2.517)
	b -554.986 (142.850)	b 7.308 (1.102)	b -1615.049 (964.870)	b 3.915 (0.404)		b -1551.070 (461.006)	b 2.464 (0.197)	b -20985.723 (12509.773)	b 1.710 (0.451)
	c -376.551 (264.520)	c 909.095 (25.369)	c 2770.855 (2994.313)	c 699.653 (27.477)		c 2102.137 (1289.679)	c 1008.063 (89.924)	c 100196.528 (884578.479)	c 721.925 (221.347)
	R^2 0.954	d 3.799 (0.277)	R^2 0.971	d 5.137 (0.326)		R^2 0.993	d 6.342 (0.718)	R^2 0.981	d 8.205 (2.288)
	R^2 0.990		R^2 0.996			R^2 0.999		R^2 0.991	
Nagpur	a -0.654 (0.302)	a -5.432 (0.826)	a -21.423 (36.536)	a -5.630 (0.179)	Yavatmal	a -0.430 (0.186)	a -3.680 (0484)	a -163.516 (624.914)	a -12.901 (2.494)
	b -474.533 (71.881)	b 4.492 (0.545)	b -3403.655 (5231.287)	b 3.918 (0.206)		b -425.092 (63.709)	b 4.455 (0.460)	b -22239.695 (83138.55)	b 1.826 (0.245)
	c -379.467 (131.595)	c 955.135 (65.309)	c 10280.264 (21817.027)	c 550.281 (9.426)		c -578.254 (88.375)	c 910.315 (54.538)	c 113261.688 (508355.443)	c 941.232 (180.352)
	R^2 0.985	d 5.594 (0.801)	R^2 0.968	d 5.682 (0.155)		R^2 0.985	d 3.718 (0.470)	R^2 0.993	d 12.842 (2.371)
	R^2 0.996		R^2 0.999			R^2 0.997		R^2 0.997	

a,b,c,d are regression statistics; R^2 is coefficient of regression



(a) (b)

Fig. 4: Residual error plot for generated (a) Boltzmann and (b) Logistic models in describing cumulative mean number of *H. armigera* larvae on pigeonpea



(a) (b)

Fig. 5: Residual error plot for generated (a) Boltzmann and (b) Logistic models in describing cumulative mean number of *H. armigera* larvae on chickpea

negative effects on demographic parameters of *H. armigera*.

Simulation of H. armigera larval dynamics

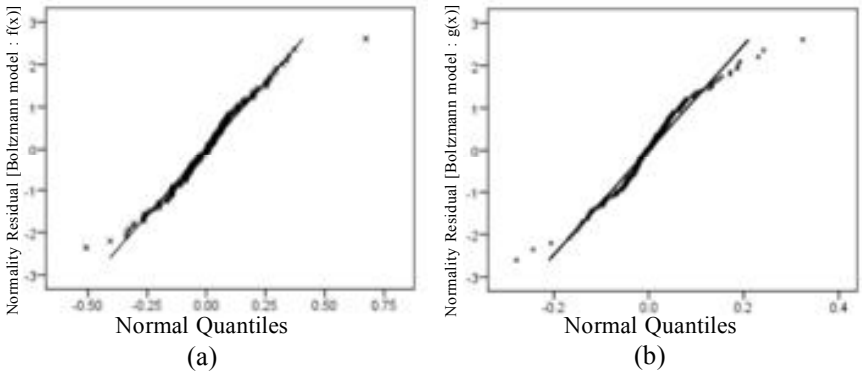
A non-linear regression was employed to generate present models, illustrating *H. armigera* cumulative mean larval incidence in 16 locations over three seasons. Regression parameters in Boltzmann (a,b,c) and Logistic (a,b,c,d) non-linear equations were estimated and presented in Table 2. Through both the equations, cumulative incidence of *H. armigera* from various locations was well described. The -initial appearance (biofix) of *H. armigera* larvae on pigeonpea, across the locations and years was noticed in the range of 86-113 GDD (biofix - 40 SMW) accumulation, while in chickpea between 62 and 86 GDD (biofix - 43 SMW) accumulation. Both Eq.(1) and Eq.(2) were fitted with estimated regression parameters, observed and forecasted cumulative larval abundance in relation to accumulated GDD of *H. armigera* (Fig.2,3). Under natural (field) conditions, mean larval incidence on pigeonpea reached ETL (≥ 1 larvae per 3 branches) at 629 GDD while, Eq. (1) and Eq.(2) forecasted the ETL at 553 and 629 GDD, respectively (at LDT - 12.6 ºC and biofix - 40 SMW). Similarly, natural cumulative mean larval incidence in chickpea reached ETL (≥1 larvae per one meter row length) at 378 GDD accumulations whereas, Eq. (1) and Eq. (2) forecasted the ETLat 305 and 378 GDD accumulations, respectively (at LDT - 12.6 ºC and BIOFIX - 43 SMW). The resulted residual (error term) from developed models were illustrated in scattered plots. Error terms (μ_i) were noticed in increasing trend throughout the *H. armigera* larval incidence in pigeonpea (Fig.4) and chickpea (Fig.5). In most cases, error term (resulted from residual) was normally distributed for the non-linear regression functions developed (Fig.6 and 7).

The accumulated GDD estimated through logistic model for *H. armigera* in pigeonpea (629 GDD) and chickpea (378 GDD) crops to reach ETL was matched exactly with observed accumulated GDD needed for *H. armigera* under

Table 3: Regression characteristics and statistical information criteria values of two-nonlinear regression models

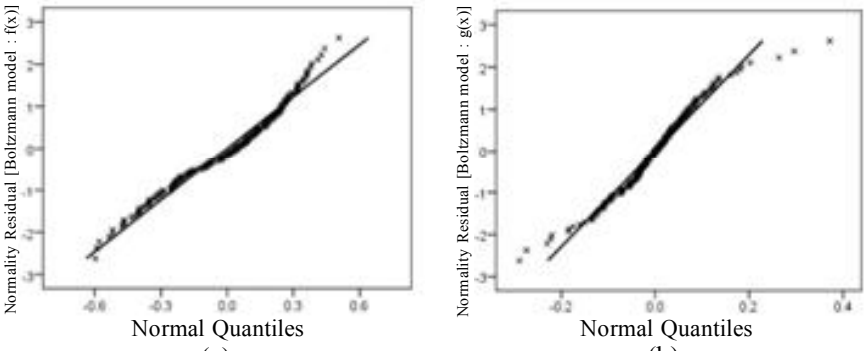
Location	Pigeonpea					Chickpea				
	Regression characteristics		Statistical informationcriteria			Regression characteristics		Statistical information criteria		
	Model	Adj. r^2	F	AIC	BIC	Model	Adj. r^2	F	AIC	BIC
Ahmednagar	Boltzmann	0.993	2240.484	-62.206	-60.661	Boltzmann	0.993	1891.830	-43.226	-41.947
	Logistic	0.995	2819.346	-65.842	-64.297	Logistic	0.999	12342.343	-69.332	-68.054
Akola	Boltzmann	0.987	944.621	-53.716	-52.586	Boltzmann	0.968	400.158	-31.478	-30.200
	Logistic	0.998	4932.957	-74.961	-73.831	Logistic	0.998	6635.757	-70.018	-68.739
Amravati	Boltzmann	0.963	317.531	-36.797	-35.667	Boltzmann	0.960	362.164	-42.014	-40.469
	Logistic	0.995	2276.282	-61.643	-60.513	Logistic	0.998	8228.520	-90.827	-89.281
Aurangabad	Boltzmann	0.986	771.538	-63.001	-62.031	Boltzmann	0.966	369.361	-39.076	-37.798
	Logistic	0.986	767.436	-62.939	-61.969	Logistic	0.997	3878.977	-71.187	-69.909
Buldana	Boltzmann	0.988	957.142	-67.711	-66.581	Boltzmann	0.984	814.579	-51.998	-50.720
	Logistic	0.996	3363.493	-83.837	-82.707	Logistic	0.998	5730.989	-78.960	-77.682
Chandrapur	Boltzmann	0.951	272.488	-35.984	-34.568	Boltzmann	0.968	3.98.939	-34.447	-33.169
	Logistic	0.990	1335.942	-58.723	-57.307	Logistic	0.996	2884.377	-61.429	-60.151
Jalgaon	Boltzmann	0.973	462.007	-46.669	-45.391	Boltzmann	0.962	436.774	-36.139	-34.358
	Logistic	0.979	592.797	-50.002	-48.724	Logistic	0.995	3356.708	-71.722	-69.942
Nagpur	Boltzmann	0.983	766.465	-48.176	-46.897	Boltzmann	0.965	359.186	-28.336	-27.057
	Logistic	0.996	3084.726	-67.343	-66.065	Logistic	0.999	10457.537	-74.645	-73.367
Nanded	Boltzmann	0.998	5748.612	-82.787	-81.371	Boltzmann	0.988	1102.278	-36.374	-35.096
	Logistic	0.999	16038.325	-98.134	-96.718	Logistic	0.998	6193.939	-60.292	-59.013
Nashik	Boltzmann	0.926	150.998	-50.678	-49.548	Boltzmann	0.912	105.110	-30.375	-29.579
	Logistic	0.953	243.435	-56.204	-55.074	Logistic	0.985	672.581	-49.274	-48.479
Osmanabad	Boltzmann	0.967	351.528	-25.269	-24.140	Boltzmann	0.989	1121.365	-39.074	-37.796
	Logistic	0.998	5240.291	-59.645	-58.515	Logistic	0.999	12806.852	-72.890	-71.620
Parbhani	Boltzmann	0.972	425.014	-42.276	-41.146	Boltzmann	0.967	381.438	-34.074	-32.796
	Logistic	0.998	5512.549	-74.978	-73.849	Logistic	0.998	7173.918	-74.330	-73.052
Pune	Boltzmann	0.998	6513.289	-69.322	-68.192	Boltzmann	0.987	1020.214	-39.241	-37.962
	Logistic	0.999	10830.404	-75.915	-74.786	Logistic	1.000	28695.057	-85.639	-84.361
Wardha	Boltzmann	0.998	5915.466	-71.629	-70.499	Boltzmann	0.969	404.529	-35.706	-34.428
	Logistic	0.997	4234.001	-67.301	-66.171	Logistic	0.998	8275.227	-77.184	-75.906
Washim	Boltzmann	0.992	1515.985	-54.774	-53.644	Boltzmann	0.979	567.510	-35.571	-34.441
	Logistic	0.999	9883.284	-78.987	-77.857	Logistic	0.990	1174.873	-44.772	-43.642
Yavatmal	Boltzmann	0.983	702.383	-54.844	-53.714	Boltzmann	0.992	1795.270	-45.222	-43.806
	Logistic	0.997	4233.048	-77.858	-76.728	Logistic	0.996	3831.127	-56.477	-55.060

Values in bold script indicate better model performance,with respect to statistical criteria. **Fig. 1:** Outline map of Maharashtra state representing sampling sites



(a) (b)

Fig. 6: Residual normality probability plot for generated (a) Boltzmann and (b) Logistic models in describing cumulative mean number of *H. armigera* larvae on pigeonpea



(a) (b)

Fig. 7: Residual normality probability plot for generated (a) Boltzmann and (b) Logistic models in describing cumulative mean number of *H. armigera* larvae on chickpea

natural (field) conditions. However, Boltzmann model has estimated ETL too early than natural observation. This precise forecast behavior of logistic model was attributed to its parameter estimates. Additional inclusion of abiotic and biotic factors in logistic model, might improve the precision inforecasting *H. armigera* larval incidence. Shivani *et al.* (2019) experimental evidence demonstrated that 77% variability in *H. armigera* larval population on tomato was accounted by weather parameters particularly maximum temperature, morning and evening relative humidity. Furthermore, present models have been established on a single factor i.e., day air temperature and, incorporation of additional pest developmental events in relation to other weather parameters could improve robustness towards deep understanding of *H. armigera* ecology and survival as an agricultural pest.

Statistical evaluation of models

Both model performances were ranked based on Adj. r^2values. Higher accuracy in forecasting *H. armigera* larval incidence has been described by logistic model (Eq.(2)) in both crops across the locations, except Aurangabad and Wardha locations in pigeonpea where Boltzmann model (Eq.(1)) was found to fit better. Lower statistical information criteria (AIC and BIC) values for logistic models in presents study showed better performance over Boltzmann models in most of the locations across the crops and this observation was in consonance with Damos and Savopoulou-Soultani (2010). Estimated AIC and BIC values are based on OLS instead of likelihood, which additionally provide simplified statistical tools for model selection. Timely forecasting of *H. armigera* larval incidence based on larval phenology in pigeonpea and chickpea crops was quite useful for decision making in insect pest management.

Two key factors, accumulated GDD and 'biofix' aided in the development of effective forecast models. In the current study, logistic model outperformed the boltzmann model across the locations, seasons and crops. This implies that our logistic model can be a better alternative to the existing conventional models, which are developed based

solely on temperature as a factor for forecasting *H. armigera*on pigeonpea and chickpea in Maharashtra State, India.

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